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UPWELLING IN THE GULF OF LIONS

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ct. The hydrological and meteorological ristics of the Gulf of Lions are such elling occurs with no bias due to tides g longshore circulation. The sky is gen- loud-free, an uncommon feature in an g area that allows extensive use of sate- frared data. The observations are ade- compute mean maps of the sea-surface ure during upwelling events. Undoubtedly g is much more intense along straight segments 10 to 20 km long than near capes l bays; upwelling locations are mainly to the coastline shape. The imagery also that the surface circulation varies in space and time; this has been veri- *in situ* measurements, as has the exis- wind-induced eddies in the surface layer. e images from the largest upwelling re- orthwest Africa, Oregon, Peru) show sim- tial variability of the sea-surface tem- , but because of the rectilinear coast- d except for some specific areas charac- by highly variable wind stress or bottom hy, plumes and edies move slightly along- d are not characteristic of a mooring The geomorphology of the Gulf of Lions is t eddies have a fixed location and mean are significant. Upwelling studies in as might be simplified by the reduction perturbations associated with the general ion and geostrophic turbulence.

Introduction

s of *in situ* recorders have recently been g sections perpendicular to the coast in the largest upwelling areas (northwest Oregon, Peru); many of the papers pre- during the 1980 International Symposium al Upwelling dealt mainly with the circu- in a vertical plane, although it is now generally accepted that upwelling is a three-dimension phenomenon. Some of the papers discussed observations from minor upwelling areas (northeast America, southwest Africa, etc.) where there are generally significant relationships between upwelling location and bathymetry. A fine-scale study of upwelling in the Gulf of Lions (Millot, 1979) shows that its occurrence is not related to the very smooth bathymetry (Fig. 1) but only to the coastline configuration. The purpose of this paper is to demonstrate that, at least in the Gulf of Lions, the trend of the coastline is the main determinant of the sea-surface temperature and the surface-current distribution in the coastal zone.

The first concepts of the structure of upwelling in the Gulf of Lions were suggested by infrared satellite imagery collected from 1975 to 1978. A four-mooring experiment was conducted near an upwelling center for a 3-month period during the 1978 summer. The sub-surface moorings supported two Aanderaa current meters at depths of 10 m beneath the surface and 5 m above the bottom and a thermistor chain between them; the four moorings were in depths of 43 (A), 98 (B), and 74 m (C and E) (Fig. 1). The mooring at Sta. C was destroyed by a trawler two days after its setting, and bottom current meters at Stas A and E failed after 2 months and 2 weeks, respectively.

An image from the NOAA 5 radiometer is formed by a combination of the satellite's motion and the scanning movement of the radiometer from horizon to horizon in a direction perpendicular to the track. The spatial resolution at the nadir is ca. 1 km^2 when the radiometric resolution is 0.5^oC (noise is ca. 1.5^oC). Data provided by the Centre de Météorologie Spatiale in Lannion are processed by the Centre de Télédétection et d'Analyse des Milieux Naturels in Sophia Antipolis (both are French centers). The

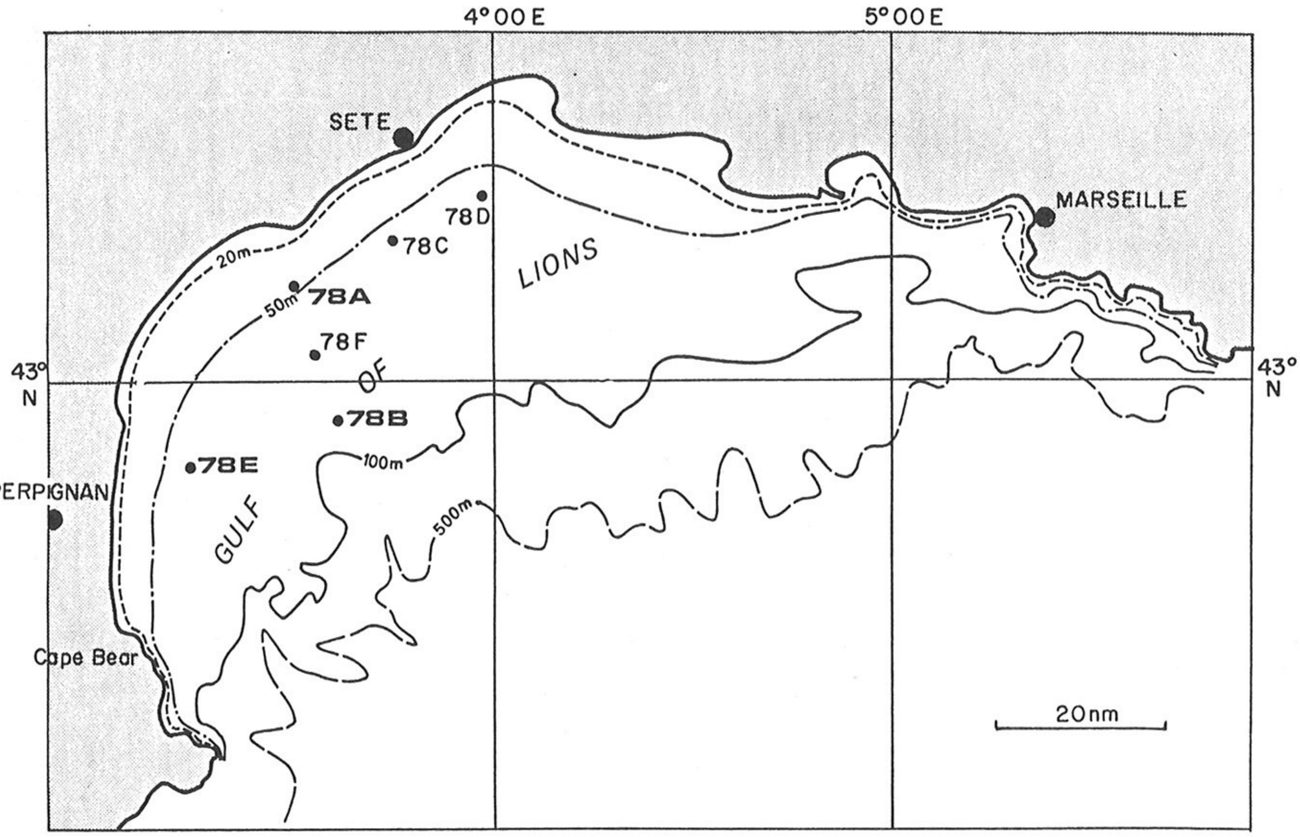

Fig. 1. The study area.

data processing includes the computation of temperature, the smoothing of images, the drawing of thermographic maps, and the geometric correction due to the earth's spin and the curvature of the surface. Noisy data are smoothed with a bidimensional filter of the moving average type, which is conditioned by the importance of local gradients with respect to noise (Albuisson, 1976).

The relative sea-surface temperatures are determined with an accuracy of 0.5°C for a 3-km resolution (Albuisson, Pontier, and Wald, 1979) so the data are reliable in the study of horizontal thermal gradients and their spatial distribution. To make the images superimposable ($\pm$ 1 km^2) on each other, they are geometrically corrected from landmarks (Albuisson, 1978). Images are two-dimensional arrays, and it is possible to compute a time-averaged value for each geographic point. Problems such as the elimination of small clouds, the calibration of the radiometer, and the atmospheric absorption have been solved (Wald, 1980), and it is shown that mean thermal gradients are defined with satisfactory accuracy.

The Observations

Details of the meteorological and hydrological regimes in the Gulf of Lions, the observations, and specific features of the upwelling events are given in Millot (1979); only the main characteristics will be discussed briefly.

The Gulf of Lions (Fig. 1) is in the northwestern Mediterranean Sea. It has a roughly semi-circular shape with a radius of about 100 km; the bathymetry of the continental shelf is quite smooth, as is the topography of the coast. The gulf is the most windy region of the entire Mediterranean basin; associated with cyclogenesis over the northern part of Italy, strong (daily speeds range from 10 to 20 m/s) and transient northwesterlies frequently blow for periods of 1 to 10 days all year long. The main geographic feature is a set of three mountain masses separated by two valleys, which make the wind stable in direction. During summer, the thermocline in the coastal zone lies at about mid-depth and separates a bottom layer (minimum temperature about 13.5°C) from an upper layer with a mean temperature of about 20°C. Surface temperatures reach maxima around 25°C.

Satellite data. The temperatures (from infrared sensing) in Fig. 2 follow by about 1 day the onset of a northwest pulse. On a larger scale, it is clear that upwelling is occurring along coastlines where an observer with his back to the wind has the sea mainly on his right; winds per-

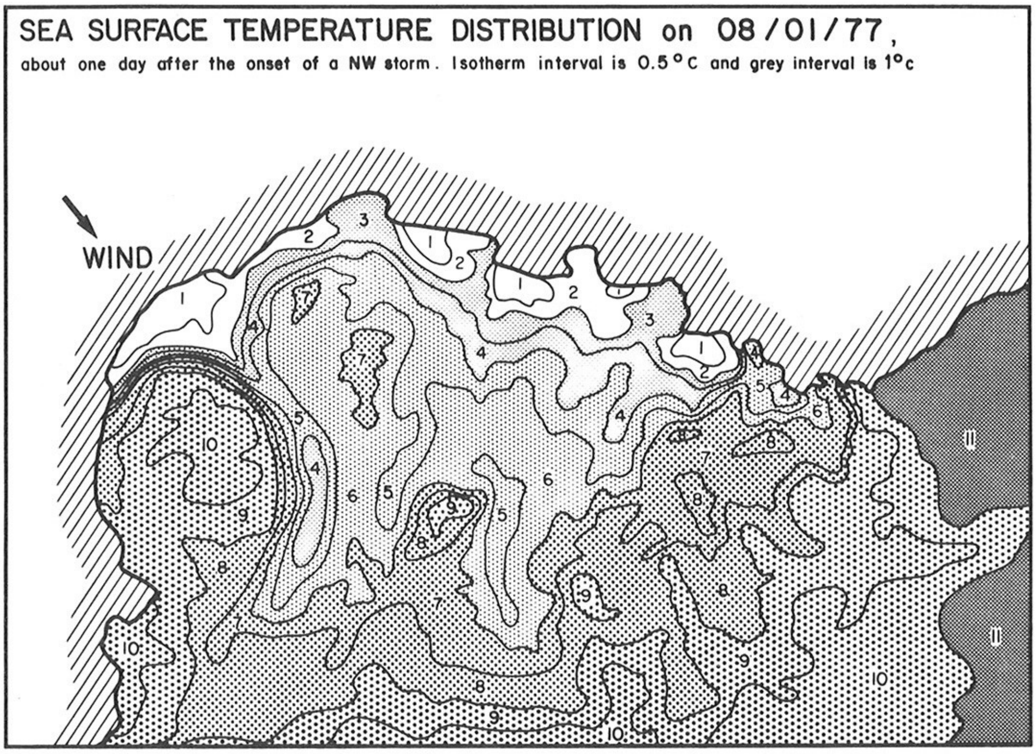

Fig. 2. The infrared satellite view taken on the 1st of August 1977 at about 09:00 UT. Note the discontinuity of upwelling and the surface circulation suggested by the structure of the isotherms.

pendicular to the coast also create upwelling, as in the vicinity of Sta. A. As a rule, no sea-surface temperature gradient appears in the southwestern part of the gulf (downwelling). On a smaller scale, upwelling is highly discontinuous, and actual source-points of cool water are clearly distinguishable. If it is considered that the coastline forms a series of curves (segments 10 to 20 km long are separated by capes and small bays), it appears that upwelled water spreads out along straight segments more than near smaller features; this statement implys that the upwelling centers are on the leeward side of some capes and on the windward side of others. The largest sea-surface temperature gradients induced by the wind in the gulf occur near shore in the vicinity of capes and bays; they are of the order of 1°C/km and are directed alongshore. Plumes of cool water drift seaward from some of the upwelling centers. Among the 100 views of the area we have, 15 are cloud-free and show all the centers; the time-lag between the onset of the wind and the passage of the satellite ranges from 1 to 3 days, but this does not seem to be important with respect to the sea-surface temperature structure. To produce a statistical picture of upwelling in the gulf, we have used the summation program presented in the introduction. The results of the summation are shown in Fig. 3.

The strongest temperature gradients in the various views are not in exactly the same place, and they are smoothed by the summation. Nevertheless, the main features described above appear clearly in Fig. 3: distinct upwelling centers (i.e., low temperature centers) are along straight coastal segments and large temperature gradients are observed in the vicinity of capes and bays; plumes of cool water that have drifted seaward from the largest upwelling centers also appear to have a roughly fixed location.

In situ *data*. Figs 1 and 3 show that mooring points were located near an upwelling center (A), roughly in the axis of a plume of cool water that drifted seaward (B), and on the edge of the upwelling zone (C and E). The array was intended to define with a sufficient accuracy features suggested, for instance, by Fig. 2, such as an anticyclonic eddy in the southwestern part of the gulf, and complex wind-induced motions on the edges of the upwelling center. Wind measurements were obtained in Sète, Perpignan, and at Cape Bear (Fig. 1).

Fig. 4 shows daily winds, currents, and some temperature records during a pulse from September 5 to 13. We choose to describe this event because it shows both classical and uncommon features. The onset of the wind was between 00:00 and 06:00 h on September 5. Its direction was roughly the same at the two southern stations, but the wind blew at Sète from NW to N (a classical feature). The wind stopped on September 14

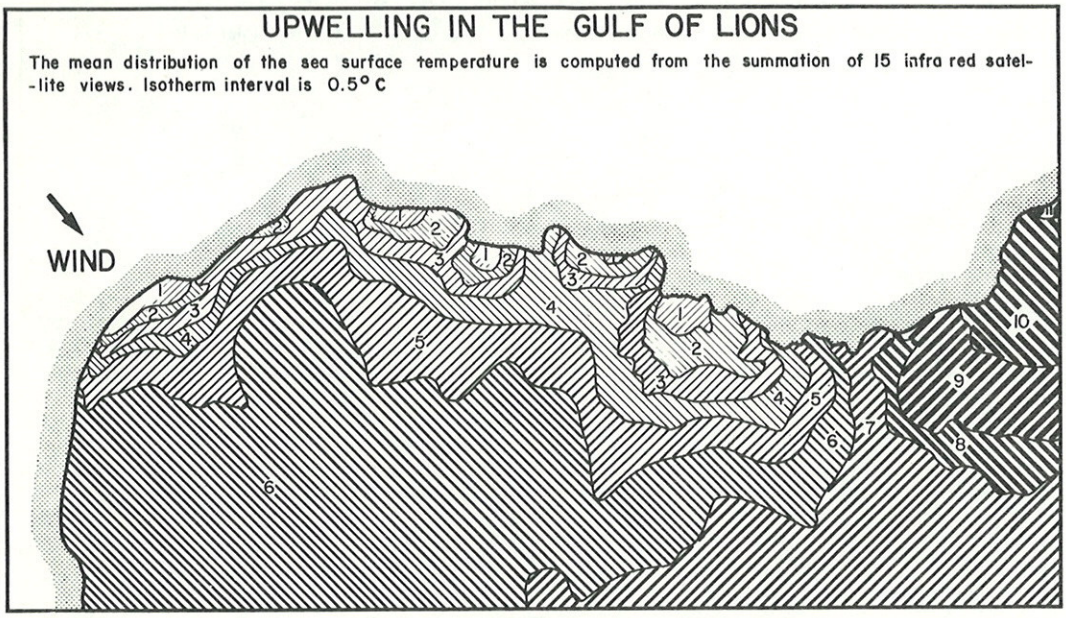

Fig. 3. The mean distribution of the sea-surface temperature obtained by summation of 15 satellite views. The location of upwelling along straight coastal segments is actual and offshore jets of cool water also have a roughly stable location.

and then blew again for 1 day. Wind speeds over the studied area during the pulse ranged from 10 to 15 m/s.

The temperature measured 10 m beneath the surface at point A was decreasing after 1 day of wind, and the whole column was only slightly stratified after about 3 days. The 30-m deep record is disturbed only by inertial internal waves (Millot and Crepon, 1981). At B, the deeper record reveals that the temperature was increasing quickly on September 7, when a record from a shallower depth shows a smooth decrease up to the 8th; both records then increase and nearly reach the values measured at the 10-m depth before the pulse. Such features show that temperature variations due to advection and oscillations of the thermocline are larger than those due to mixing. Downwelling is evident at E and the shallower temperature is roughly constant: this supports the idea that the thermocline at Sta. E was deeper than at Sta. B. The temperature records and wind data are consistent with current measurements.

All the current speeds were small before the onset of the wind and on the 5th when the wind was moderate. As the northwest wind increases, the current pattern becomes consistent with the classical scheme (see below), i.e., surface currents are to the southeast at points A and B when the surface current at E is large and northward (opposed to the theoretical Ekman transport); currents in the whole bottom layer are northeastward. So upwelling was increasing near A and the cool water upwelled to the surface drifted roughly from A to B in the direction of the wind. Warm water moving northward at E turns to the right and joins the offshore current of cool water. From the 8th, the wind blew from the north-northeast quadrant in a region north of the study area, and the surface current at A rotated to the southwest from the 10th. The current was then opposed to the current at E, which deviated offshore. Near B the current was not very different, but the water characteristics had changed. The offshore jet of cool water passed across B in the afternoon of the 8th, and then was located between B and E. Waters moving seaward at B and E from the 10th were warm, i.e., waters of the surface layer. Speeds were significant and corresponded to displacements larger than 30 km a day at B, about 40 km offshore. So, during the second part of the wind event, a cyclonic wind-driven circulation occurred in the northern part of the study area. But the most surprising feature described above is the occurrence of an upwind surface current at E when the wind field was roughly homogeneous, that is when the wind was blowing from the northwest over this part of the gulf.

To demonstrate that the above wind-induced feature is common we have computed mean currents during two sets of typical meteorological conditions (northwesterlies either blow or not, whatever the wind stress may be). Preliminary results were obtained by considering only the strongest winds (28 days out of 85). Upon considering all days and parts of days when strong or moderate northwesterlies were blowing, the statistics for

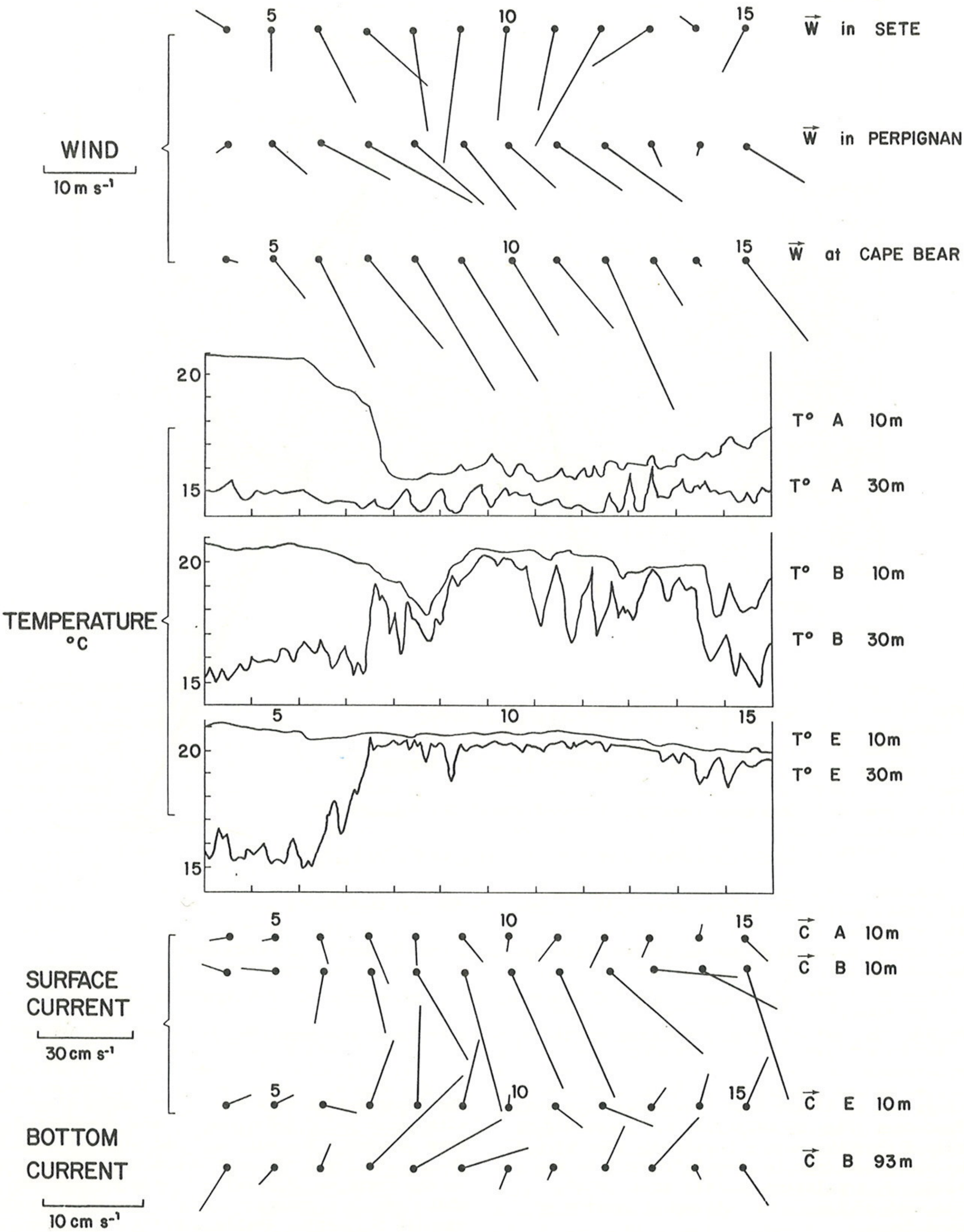

Fig. 4. The daily winds and currents and some temperature records from September 4 to 15. Vectors are plotted in such a way that the vertical axis is north-south.

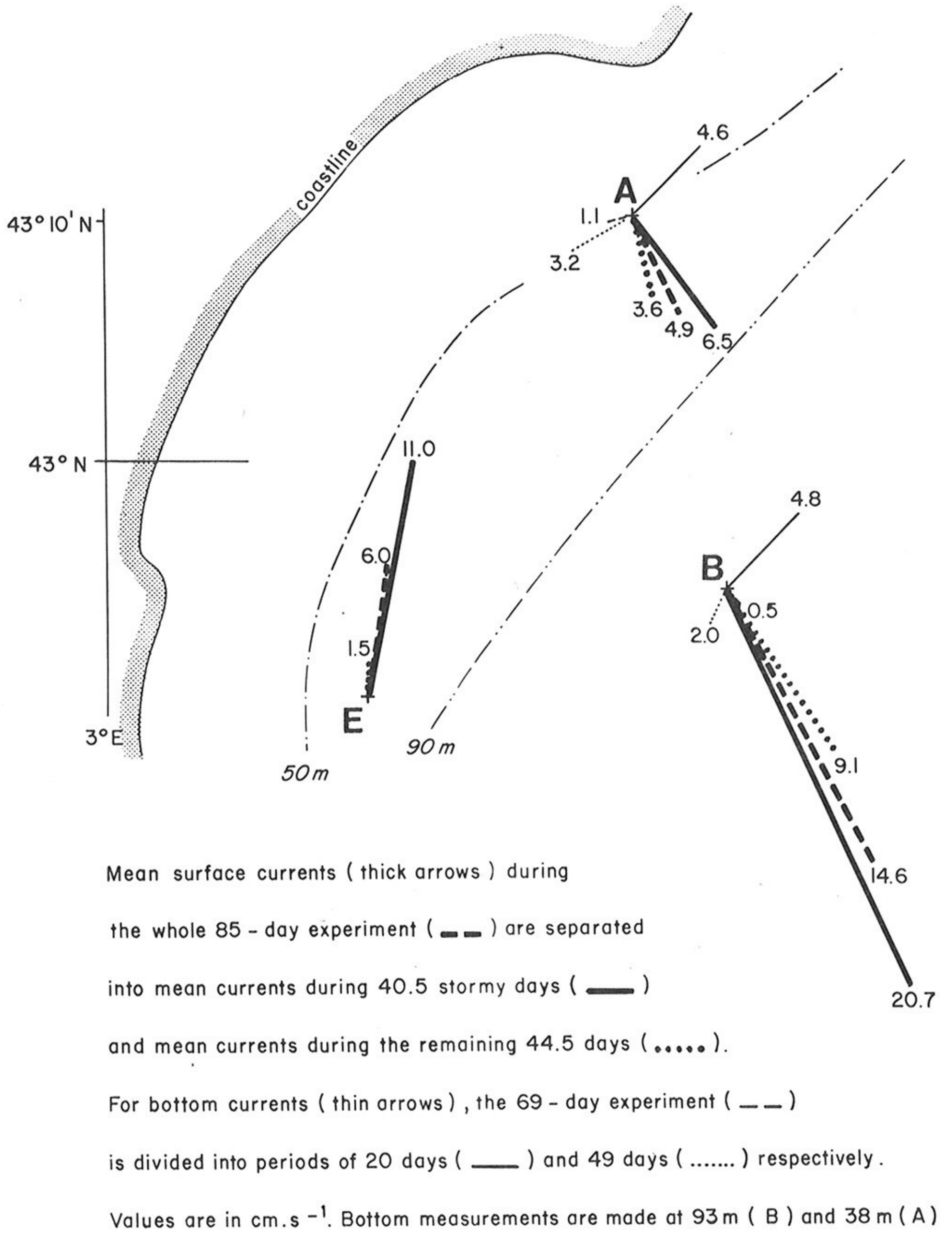

Fig. 5. Dependence of mean surface and bottom currents upon the occurrence of northwest storms.

40.5 days out of 85 are more convincing than the previous ones (Fig. 5) mainly at E. It should be emphasized that the mean circulation observed out of the stormy periods is also influenced by the wind-induced circulation (mainly at A and B), because such eddies do not disappear as soon as the wind drops.

Measurements were obtained at A and B in the bottom layer (Fig. 5) (at depths of 38 and 69 m, respectively) for a 69-day period. As expected, the layer reacts only to the strongest winds and with about 1-day delay, so we have considered 20 days of wind. The wind-induced mean currents in the bottom layer appear to be strong and opposed to the currents observed during quiet periods, which are in agreement with the general circulation in the region (Millot, 1979). The mean temperatures at 10 m during all the experiments were 17.44°C at A, 19.28°C at B, and 19.48° at E. Thus, upwelling was an influence at A, but water moving northward at E and southeastward at B had roughly the same temperature as the undisturbed surface layer.

Discussion

A first question is why does upwelling, at least in the Gulf of Lions, spread out along straight coastal segments more than in the vicinity of smaller scale features? A second question is how can the wind-induced current field be so heterogeneous in such an area?

Numerical models (Hua and Thomasset, 1980) have been used to test the relationship between upwelling location and the coastline shape; even if the geographic condition is schematically approximated, results are satisfyingly coherent with observations. However, the models do not show the northward flow at Sta. E. The hypothesis that might be advanced is that when an upwelling-favorable wind blows in the vicinity of a straight coast, all the particles of the surface layer are subjected to the same forcing; without perturbations due to geostrophic turbulence, the result is that the upwelling must spread out. In a small bay, however, the wind may be upwelling-favorable in a small area and downwelling-favorable not far away. The current field is much less homogeneous than in the vicinity of a straight coast; complex circulations probably occur and reduce both up- and downwellings both in small bays and near capes. Let us discuss, for instance, the features occurring in a non-rotating fluid in which a semi-infinite barrier is supposed to schematize a cape. If the wind is blowing in a direction perpendicular to the barrier orientation, it is clear that upwelling (downwelling) will spread out along the leeward (windward) coast. But around the origin of the barrier, neither upwelling nor downwelling is expected, and strong currents will characterize this singular area.

Considering from our data set the structure of the current field induced by the wind in the surface layer, we have to start from the upwelling location; that this location is related to the coastline, to the wind field, or to the bathymetry is not to be taken into account. The fact is that upwelling is there because the offshore current in the area is stronger than in the neighboring areas. In the Gulf of Lions, an offshore drift current is regularly observed at B, generally at A, and infrequently at E. The temperatures in Fig. 2 show an anticyclonic eddy, which is consistent with the northward wind-induced current at E. How such an eddy is created by the wind is not easily explained, and we must consider parameters other than the wind stress. First, the special structure of the gulf: warm waters accumulate in the southwest part and perhaps tend to flow toward areas where the sea level is lower as, for instance, upwelling areas. Second, the density gradients between the upwelling center and the other areas: the offshore drift current is compensated by the pumping of heavy bottom water, or by the advection of surface water, the density of which is equal to or lower than the density in the seaward flow. What is the largest compensating phenomenon? In our opinion, it is probable that the pumping of bottom water occurs first; counter-circulations and eddies may then arise in the surface layer to compensate the offshore drift. The satellite imagery of all the upwelling areas shows that the sea-surface temperature distribution and the associated circulation are highly discontinuous. Along the straight coastlines of the largest upwelling regions, the structures may move alongshore and make difficult a detailed analysis of current records, explaining why only mean currents can readily be discussed.

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